

Final Report

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**INFRARED AND PASSIVE MICROWAVE RADIOMETRIC SEA
SURFACE TEMPERATURES AND THEIR RELATIONSHIPS TO
ATMOSPHERIC FORCING**

Report Prepared

For

NASA Goddard

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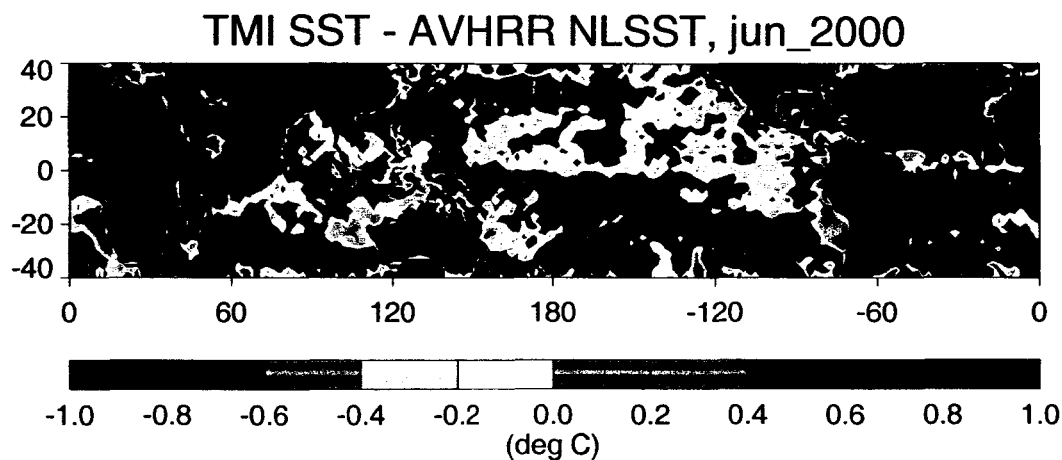
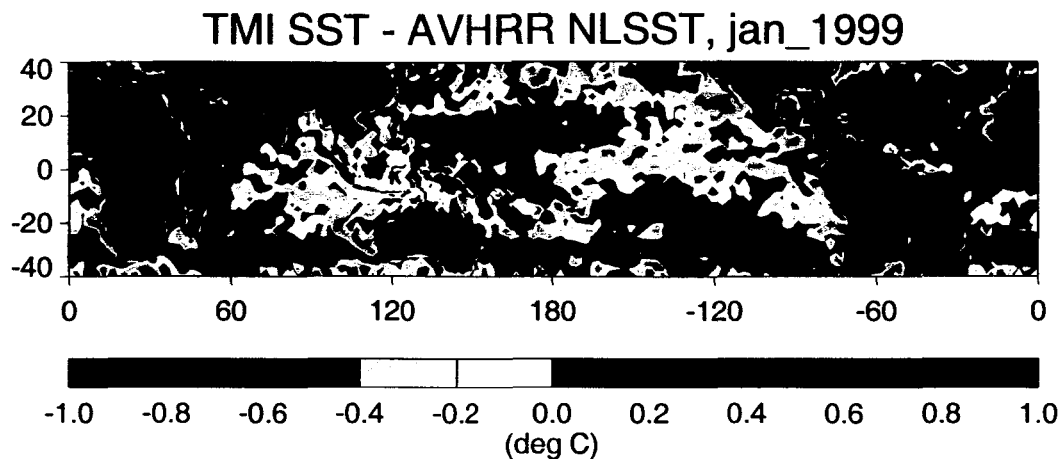
1. Introduction

The current generation of infrared (IR) and passive microwave (MW) satellite sensors provides highly complementary information for monitoring sea surface temperature (SST). On the one hand, infrared sensors provide high resolution and high accuracy but are obscured by clouds. Microwave sensors on the other hand, provide coverage through non-precipitating clouds but have coarser resolution and generally poorer accuracy. Assuming that the satellite SST measurements do not have spatially variable biases, they can be “blended” combining the merits of both SST products. These factors have motivated recent work (e.g., Wick et al. 2004) in blending the MW and IR data in an attempt to produce high-accuracy SST products with improved coverage in regions with persistent clouds.

The primary sources of retrieval uncertainty are, however, different for the two sensors. The main uncertainty in the MW retrievals lies in the effects of wind-induced surface roughness and foam on emissivity, whereas the IR retrievals are more sensitive to the atmospheric water vapor and aerosol content. Average nighttime differences between the products for the month periods of January 1999 and June 2000 are shown in Figure 1. These maps show complex spatial and temporal differences as indicated by the strong spatially coherent features in the product differences and the changes between seasons. Clearly such differences need to be understood and accounted for if the products are to be combined.

Accounting for the sources of the differences is especially significant since the sensors effectively respond to sea surface temperatures at slightly different depths in the water column. Thermal infrared measurements at wavelengths around 11 μm sense the temperature at depths on the order of 10 μm . Passive microwave measurements at 6.6 and 10.7 GHz, however, measure the temperature at effective depths of roughly 1.7 and 0.9 mm. A proper blending technique requires that one or both measurements be adjusted to a common depth or that some knowledge of this difference be applied in the combination of the products. Extensive research has shown that the presence of the ocean skin layer can lead to significant temperature differences between these depths. The fact that different penetration depths respond to different temperatures has led to some speculation as the potential for regarding the temperature difference from the two sensors as an estimator for the bulk-skin sea surface temperature difference (ΔT). In any event, increased understanding of the depth dependence of MW and IR SST retrievals is essential for multi-sensor data blending efforts, and ultimately, for calculating true skin and bulk satellite-derived SST products.

The overall goals of this project are threefold: (1) to understand the sources of uncertainty in the IR and MW SST retrievals and to characterize the errors affecting the two types of retrieval as a function of atmospheric forcing; (2) to demonstrate how representative the temperature difference between the two satellite products is of ΔT ; and (3) to apply bias adjustments and to devise a comprehensive treatment of the behavior of the temperature difference across the oceanic skin layer to determine the best method for blending thermal infrared and passive microwave measurements of SSTs.



2. Strategy Overview

The general method that was adopted to determine the MW and IR SST differences and their relationship to atmospheric forcing was to use representative IR and MW sea surface temperature products and independent in situ observations from drifting and moored buoys. Differences were computed between the two satellite products and between each satellite product and the buoy observations. For the comparisons with buoys, sets of matches were constructed where the satellite and in-situ observations were collocated within 25 km and 1.5 hours. For the satellite intercomparisons, separate daytime and nighttime grids from each day were differenced. The corresponding difference grids were then averaged over periods from 1-3 months. Two years of data from 1999-2000 were used in the comparisons.

The specific methodology used throughout this project varied significantly from year to year, as a certain amount of iteration was needed during the course of this study. As a result, we will summarize the specific objectives accomplished each year independently.

Year 1 (2001-2002):

During the first year we decided to focus on implementing an algorithm for retrieving MW SSTs from the Scanning Multichannel Microwave Radiometer (SMMR) brightness temperatures (BTs). The computations were performed using a radiative transfer (RT) equation provided by Eni Njoku (NASA). The infrared SSTs were estimated from the 4 km Global Area Coverage (GAC) AVHRR BTs, using the same coefficients of the operational AVHRR non-linear SST (NLSST) algorithm from the Naval Oceanographic Office. Model parameters were tuned using a cloud-free portion of the Arabian Sea. Mean bias and rms errors between SMMR and AVHRR GAC SST differences were deemed worthy to pursue further comparisons over larger regions.

Further analyses were done using monthly-averaged $2^\circ \times 2^\circ$ grids in the Pacific Ocean. Similar comparisons using TMI SST data were also made. The latter comparisons, however, showed significant SST bias and rms errors in the differences relative to the SMMR SSTs. Potential sources of error included uncertainties in the geophysical MW model, poor choices in some of the assumptions made in the iterative scheme used to solve for the SST from the transfer equation, calibration drifts of the SMMR instrument, as well as residual cloud contamination in the AVHRR GAC SSTs.

Preliminary work in developing a skin-only IR SST product from the AVHRR GAC BTs was also done using a new set of coefficients provided by Dr. Peter Schluessel (EUMETSAT). The new coefficients, however, produced unrealistically cold skin temperatures. We ended the first year with the realization that new skin SST retrieval coefficients were much needed in order to pursue objective (2) of this proposal.

Year 2 (2002-2003):

The inability to obtain accurate MW SSTs from SMMR, led us to adopt the TRMM Microwave Imager (TMI) SST retrievals prepared by Remote Sensing Systems (e.g. Gentemann et al., 2004) as the passive microwave product. The IR bulk SST product remained as before. As for the GAC AVHRR skin-only SST product, a new set of coefficients was derived based on a RT model for SST retrievals (Zavody et al., 1995) and a globally representative suite of over 3000 radiosondes provided by Dr. Ian Barton (CSIRO). Validation analysis of the theoretically-derived skin-only SST product using in-situ radiometric skin temperatures from the MAERI interferometer (Peter Minnett, RSMAS) resulted in an estimated rms SST error of $\sim 0.05^\circ\text{C}$ for the Equatorial Pacific, indicating the ability of this type of algorithm to provide adequate regional skin SST estimates.

New comparisons among the three different SST products were done on monthly-averaged $2^\circ \times 2^\circ$ grids in fixed regions of the Pacific and Atlantic oceans. Differences between the TMI SST and the skin-only GAC AVHRR SST ranged between -2 and 2°C . In order for the positive average differences to be consistent with the overall observed cool skin of the ocean, their magnitudes should be $\sim O[0.3-0.5^\circ\text{C}]$. In previous studies relative to buoys (Wick et al., 2003), we demonstrated the presence of residual effects on the TMI SST products due to wind speed, total column water vapor and in-situ SST. To further examine the magnitude of the SST differences between the TMI and AVHRR skin SST products, bias adjustments were applied to the TMI retrievals to account for each of these residual dependencies. It was found that the bias adjustments lower the magnitude of the differences between the products (-1.5 and 1.5°C) but not significantly enough to be consistent with experimentally measured bulk-skin differences.

It became clear from these comparisons that some of the large discrepancies in the different SST products were due in part to deficiencies in our computation of AVHRR GAC SSTs resulting from residual cloud contamination in the GAC BTs. We opted then for a different IR SST product that had a cloud-filtering procedure already incorporated in it. In the NOAA operational procedure (McClain et al., 1985) several tests are applied to identify cloudy pixels. This choice excluded the possibility of comparing differences with respect to the IR skin SST product, but by eliminating a source of uncertainty and comparing algorithms representative of temperatures derived at roughly the same depths, it was possible to concentrate on additional atmospheric forcing likely to be on effect.

Year 3 (2003-2004):

Since the biases in the IR SST were sufficiently large to dominate the differences impeding our capability to detect potential skin layer temperature gradients, it was necessary to compare both sets of satellite measurements with direct SST measurements from buoys to determine the absolute accuracy of the products.

The infrared product adopted for this part of the project was the operational AVHRR non-linear SST (NLSST) retrievals (May et al., 1998) from the Naval Oceanographic Office (NAVOCEANO). This product ensures that the IR SSTs are derived from only high quality, cloud-free pixels. The passive microwave product remained to be the TMI SSTs. The buoy observations were drawn from an archive of NCEP GTS surface marine data maintained at the NOAA Climate Diagnostics Center. Extensive additional quality control was applied to the buoy data to eliminate erroneous observations and transmission errors. The comparisons were on monthly-averaged $0.25^\circ \times 0.25^\circ$ global grids.

As a starting point, we concentrated in regions where the satellite differed significantly from each other, indicating probable errors in the satellite fields or retrieval algorithms. Some of these regions included upwelling coastal zones, continental aerosol plumes over the ocean, and well-defined flow fields like the trade winds and ITCZ. To begin to account for the differences, potential sources of error in the retrieval were explored in detail. The matchups between the satellite retrievals and buoy observations were used to explore the dependence of errors in the retrievals with multiple geophysical variables.

Parameters found to impact the retrievals included wind speed (WS), column integrated water vapor (WV), SST, aerosols, sea level pressure (SLP), and atmospheric stability. These results were then used to derive four separate bias adjustments and uncertainty estimates as functions of the environmental parameters.

For the TMI SST retrievals, two bias adjustments were derived: (1) as a simultaneous function of wind speed, water vapor and SST (coincident estimates of these parameters are provided with the TMI data), and (2) as a function of atmospheric stability. The former represents an improvement over the separate corrections used in the previous year, in the sense that the simultaneous consideration of WS, WP, and SST better characterizes the non-orthogonal nature of the TMI uncertainties. The latter is a new result, likely to have significant repercussions. The atmospheric temperature used in the computation of the sea-air temperature differences (ΔT_{sa}) was obtained from climatological estimates (Oregon State University). For the NAVO AVHRR SSTs, two additional bias adjustments were derived: (1) as a simultaneous function of water vapor and SST, and (2) as a function of aerosol optical depth (aod). The latter was obtained from the NOAA/NESDIS AVHRR aerosol operational product. A comprehensive summary of the work in each of these areas is given in the IGARSS04 paper (Castro et al., 2004) included in this report.

By applying these bias adjustments, the overall MW-IR SST differences are smaller and less spatial coherence is observed. For the two year period covered in this study, the monthly MW and IR SST differences have achieved accuracies of 0.3°C rms (after bias corrections) with zero biases. Despite the improvement, differences between the products can still be observed. The remaining differences could be caused by geophysical differences related to the different effective measurement depths of the two sensors. Additional work is ongoing to explore this possibility.

As a byproduct of the estimated uncertainties, we were able to identify ranges of geophysical forcing conditions for which the bias adjustments are well defined:

$$|TMI\ SST - AVHRR\ SST| \leq 2.5^{\circ}C$$

$$WV \leq 6.5\ g/cm^2$$

$$WS \leq 17.5\ m/s$$

$$4.75^{\circ}C < \Delta T_{sa} < 12^{\circ}C$$

$$0.1\ \mu m \leq aod \leq 1.4\ \mu m$$

$$996\ mb < SLP < 1038\ mb$$

$$CLW \leq 0.04\ mm$$

By just neglecting SST data outside these regimes, a significant reduction in rms error is achieved in the SST product difference as indicated by the nighttime statistics shown in the table below for the monthly mean MW-IR SST differences presented in Fig 1.

MW SST – IR SST	No bias corrections	Inside regimes only	After bias correction
January 1999	0.17°C +0.37°C rms	0.13°C +0.33°C rms	-0.01°C+0.31°C rms
June 2000	0.21°C +0.44°C rms	0.19°C +0.36°C rms	-0.01°C+0.30°C rms

3. Research Results

We end this funding period with a better understanding of the sources of the differences between IR and MW SST products. Main accomplishments include a way to account for retrieval uncertainties resulting from actual geophysical processes through proposed bias adjustments, and hence, improvements in absolute accuracy of the individual SST products and elimination of major discrepancies of the SST differences. It is hypothesized here that major remaining sources of uncertainty are due to atmospheric stability and aerosol content for the TMI and AVHRR SST products, respectively. This implies that the corrections in the existing retrieval algorithms (wind speed and water vapor are traditionally considered as the main factors affecting the MW and IR SST retrievals respectively) are generally successful. A simple method to account for most of the rms error in the SST product difference is proposed by eliminating data points outside the regimes identified for the different atmospheric forcing conditions. The elimination of uncertainties between the products coupled with the fact that after the adjustments are applied there are some remaining differences, opens up new possibilities for the exploration of skin effects and diurnal warming corrections, which are yet to be accounted for.

An important aspect of these findings is the ongoing collaborative effort with Dr. Gary Wick of NOAA-ETL in the production of an enhanced, blended infrared and microwave, sea surface temperature product. This is a daily, pre-dawn, 0.25°-resolution SST product, which is created from the blending of the operational Advanced Very High Resolution Radiometer (AVHRR) non-linear SST (NLSST) product from the Naval Oceanographic Office (May et al., 1998), and the passive microwave SST data created by Remote Sensing Systems (Gentemann et al., 2004) using the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI). By applying our bias adjustments to the appropriate SST product before the merging, Dr. Wick has found that he can improve the rms accuracy of his blended SST product by 0.1°C, from 0.66 to 0.56°C relative to global drifting buoy measurements (personal communication). The importance of any improvement in accuracy is underlined by the fact that NPOESS SST Environmental Data Record has a stated objective uncertainty of 0.1°C. Existing corrections are also being integrated in the currently funded NOPP (National Oceanographic Partnership Program) proposal: Multisensor Improved Sea Surface Temperature (MISST) for GODAE.

In summary, a large amount of work was accomplished under the support of this grant, leading to the following publications and presentations:

- Two poster presentations (see attached mini-posters) at the 2003 AMS Conference on Satellite Meteorology and Oceanography (Castro et al., 2003; Wick et al., 2003)
- An oral presentation at the 5th GODAE High Resolution Sea Surface Temperature Pilot Project, GHRSSST-PP 2004, in Townsville, Australia
- Two short papers (Castro et al., 2004; Wick et al., 2004) that will appear in the proceedings of the International Geoscience and Remote Sensing Symposium,

IGARSS, that will take place in Anchorage, Alaska, this September (see attached copies).

- In a related area, the funding also partially supported Sandra Castro in the preparation of the publication "Further refinements to models for the bulk-skin sea surface temperature difference" (Castro et al., 2003).
- Our current efforts also include extending the IGARSS04 paper into a journal publication to be submitted in the near future.

4. Future Direction

There are some remaining points that need to be addressed. Specifically, to explore the connection between ΔT and the difference between the IR and MW SST measurements. At the start of this project, the overall magnitude of the temperature difference between the products was on the order of 1.5-2.0°C, which was in no way consistent with radiometric measurements of the skin layer effect ($\Delta T \sim O[0.3^\circ\text{C}]$). Instead, the differences were the result from both retrieval errors and actual geophysical process. By systematically applying the bias adjustments to the IR and MW SST products derived in this study (Castro et al., 2004), we were able to account for most of the geophysical processes affecting the differences reducing the noise level in both satellite products. As stated before, in the corrected M W SST– IR SST differences we have achieved zero mean bias and rms errors of 0.3°C. The remaining variability in the satellite SST product difference is now comparable, in a statistical sense, to the mean temperature differences across the skin layer. To apply corrections for the presence of ΔT , it is necessary to have global estimates of the skin temperature. With ongoing efforts in developing satellite skin SST algorithms (Proposal under contract: A Prototype System for Improving Satellite-Derived Sea Surface Temperature Through Enhanced In-Situ Validation Measurements) through the NOPP/BAA, and the knowledge gained in these studies, we are now better suited to address this problem. Further analyses are needed, however, before we can explicitly incorporate additional bias adjustments due to the complex temperature gradients occurring beneath the ocean surface or before we can accurately estimate ΔT from satellite measurements.

Errors and relation to data assimilation are being further studied under follow-on funding from the NASA physical Oceanography Program (Proposal: Comprehensive Comparison of Error Characteristics of Satellite Sea Surface Temperature Products for Application to Sensor Fusion and Data Assimilation).

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